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Astrometric reference stars: from UCAC to URAT

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Abstract. Currently available astrometric catalogs will be reviewed, and instrumentation and observational issues discussed, particularly systematic errors and their control. The U.S. Naval Observatory (USNO) CCD Astrograph Catalog (UCAC) is an all-sky astrometric survey to 16th magnitude. It was observed with a semi-automated telescope on a low budget. The second data release (July 2003) contains positions, proper motions, and photometry for over 48 million stars; the final release is expected in 2006. Design studies have been performed for a new 0.9-meter aperture USNO Robotic Astrometric Telescope (URAT) with a single chip ($\geq$ 100 Mpixel), 3 degree FOV and circular symmetric pupil. Its operation is envisioned to be fully automatic, generating stellar positions on the 5 to 10 mas level to at least 18th magnitude with a limiting magnitude of about 20 to 21. These reference stars, being on an inertial system (linked to quasars), will be very beneficial for LSST, PanSTARRS and other projects. With a few years of observing, absolute trigonometric parallaxes (5-20 mas, depending on magnitude) could be obtained for all stars accessible by URAT from an initially southern hemisphere location.

Key words: astrometry – sky surveys – instrumentation: robotic telescopes

1. Introduction

Astrometric catalog work serves 2 purposes. It is science by itself, striving toward higher accuracies in reference frame investigations, positions, proper motions and parallaxes forming the basis for solar system and galactic kinematics and dynamics studies. It also provides a larger user community with reference stars which in turn can be used for positional astronomy or many other applications like identifying sources across the wavelength spectrum. Requirements are increasing with current and future high angular resolution radio, IR and optical imaging. Just the task of identifying or matching faint targets becomes a challenge without good reference stars.

A summary of recommended astrometric catalogs is presented in section 2. The recent progress in this area will be welcomed by the many users of current and future robotic telescopes, since it provides a dense net of accurate source positions enabling even small field-of-view instruments or guide systems to verify their pointing and determine mapping parameters.

Good reference stars also can improve other, deeper surveys considerably. Section 2 also explains what is needed to get "good reference stars". For example, using UCAC (U.S. Naval Observatory CCD Astrograph Catalog) instead of Tycho-2 (Høg et al. 2000) reference stars improved the positions obtained from the Sloan Digital Sky Survey (SDSS) by a factor of almost 2 (Pier et al. 2003). Preliminary UCAC data also provided the positional "truth" (almost error free) for calibrating the 2MASS mapping and improving its reduction pipeline, although the final 2MASS catalog is strictly based on the Tycho-2 system. For the upcoming PanSTARRS and LSST projects we will have the same situation. Reference stars at least as accurate as UCAC are required, however for stars much fainter than 16th magnitude (the UCAC limit).

One of the major recent endeavors in astrometric catalog work, the UCAC project utilized an automated telescope. Instrumental features and experiences with this system are described in section 3, while section 4 outlines the next step, a future, fully robotic astrometric telescope for an all-sky survey reaching 20th magnitude and thus can directly access the defining celestial reference frame extragalactic quasars.

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2. Notes on astrometry

2.1. Recommended catalogs

Here I concentrate on current epoch position catalogs which cover (almost) the entire sky. Many astrometric catalogs contain proper motion information, thus can be applied to a wide range of epochs.

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Name of catalog	mag range	numb. of stars	σ (mas)	AW
ICRF	radio	500	0.3	5,000
HIP (1991)	≤ 12	100 K	1.0	100,000
HIP (2005)	≤ 12	100 K	20.0	250
Tycho-2	≤ 9	200 K	10.0	2,000
	≥ 9	2.3 M	80.0	400
UCAC2	9.5–14.5	10 M	20.0	25,000
	14.5–16	40 M	60.0	11,000
2MASS	IR	500 M	90.0	60,000
USNO-B	12–21	1000 M	200.0	25,000
PanSTARRS	17–23	2000 M	30.0	2.2 M
URAT	15–19	500 M	10.0	5.0 M

Table 1. Recommended astrometric and some future catalogs. The sources in the ICRF are non-moving, extragalactic (mainly QSOs). The 2MASS catalog contains no proper motions. All other catalogs listed have or will have proper motion information. The letter "K" stands for 10^3, "M" for 10^6.

Table 1 gives an overview about recommended astrometric catalogs, going from most accurate to highest density (stars per square degree). Some future catalog projects are listed at the end. The "AW" column is explained below. Acronyms not explained before are: ICRF = International Celestial Reference Frame (radio VLBI observations), HIP = Hipparcos ESA space mission (mean observational epoch 1991.25), 2MASS = Two Micron All Sky Survey (Univ. of Mass.), USNO-B = US Naval Observatory "B" catalog (from Schmidt plate scans). All these catalogs recommended for astrometric use are now combined into the Naval Observatory Merged Astrometric Database (NOMAD). A web-based interface to access NOMAD entries is in preparation at USNO.

Many presently available catalogs not mentioned in Table 1 (like FK5, SAO, PPM, USNO-A, and GSC I) are obsolete. This is now true even for a large part of Tycho-2. A Tycho-2 star fainter than about 9th magnitude if in UCAC2 has a smaller random position error in UCAC2 than in Tycho-2. The UCAC2 is a compiled catalog and was constructed to include original Hipparcos and Tycho observations as well as early epoch data which also were used for the Tycho-2 proper motions. However, UCAC2 is not complete and the systematic errors in Tycho-2 are smaller than those in UCAC2. The completeness issue of UCAC2 has been addressed recently. All Hipparcos and Tycho-2 stars missing in UCAC2 have been put together in the Bright Star Supplement (BSS); see ad.usno.navy.mil/ucac.

2.2. Astrometric weight

Often for future wide-field survey projects the "A*Omega" number (Aperture times field-of-view) is given, to indicate the capability or throughput of a telescope. For astrometry things are different. The impact of an astrometric catalog can better be judged by the "astrometric weight" (AW column in Table 1), which I define here as $AW = n / \sigma^2$, with n = number of stars in the catalog with positional accuracy of σ. Here σ is the project mean per star coordinate including systematic errors.

Errors in the proper motions lead to increasing positional errors for epochs before or after the mean observing epoch. This is very apparent in the case of the Hipparcos Catalogue. The extremely accurate positions at its mean epoch are degraded by a factor of about 20 by the year 2005. In the case of Tycho-2 and UCAC2 the astrometric weight is estimated for bright and faint stars separately. The fewer, bright stars have a higher weight. Generally, the "AW" for the "best" stars subset in all catalogs is limited by the systematic errors in that catalog.

2.3. What is a good astrometric reference star catalog?

The following properties are desirable for an astrometric reference star catalog. Its usefulness has to be judged by this metric.

Precision: small random positional errors.
Accuracy: small, external (systematic) errors, including being on an inertial reference system.
Density: sufficient number of stars per sky area.
Magnitude range: accessible by the user application.

In the case of the SDSS astrometric reductions for example, the large improvement in *density* of the UCAC data over the Tycho-2 reference stars made it possible to follow atmospheric refraction effects much better (time-delayed integration mode). Also, the *magnitude range* of UCAC enabled a direct reduction of the photometric CCDs instead of linking through short-integration time CCDs with neutral density filters.

For most of todays general imaging applications, the *density* and *magnitude range* are the most critical issues, which normally exclude the use of Hipparcos and Tycho-2 reference stars, as well as often even the UCAC data for long exposure frames at 4-meter class telescopes. In addition to *density* and *magnitude range*, *precision* and *accuracy* of a reference star catalog will become critical for future, deep, survey projects like PanSTARRS and LSST, because of the expected, high intrinsic precision of the differential, local, stellar position observations of these projects.

2.4. Error propagation

The capabilities of user telescopes are generally not fully utilized when it comes to determining positions. Often a good reference star catalog is missing, and the random errors introduced by the reference stars alone are often underestimated. The simplest term is a *zero-point offset* error σ_z for the entire CCD frame with respect to the "truth."

$$\sigma_z \geq \sqrt{\frac{\sigma_{ref}^2 + \sigma_{xyr}^2 + \sigma_{atm}^2}{n_r - p}}$$

with σ_{ref} being the error of a reference star catalog position, σ_{xyr} the error of the x,y fit position of a reference star, σ_{atm} the contribution from the turbulence in the atmosphere, n_r the number of reference stars used in the CCD frame, and p the number of model parameters in the "plate adjustment" (per coordinate). For example with σ_{ref} = 200 mas, σ_{xyr} =

20 mas, σ_{atm} = 20 mas (typical 100 sec exposure), n_r = 10, and p = 3, we get σ_z = 76 mas, although the telescope is capable of σ_{xyr} = 20 mas local astrometry. For short integration times, σ_{atm} becomes significant. This σ_z is only one of several terms from the error propagation of the plate parameters (Eichhorn & Williams, 1963). If a complex mapping model is required, these errors become much larger, particularly off-center. The σ_z can be interpreted as the precision of how well the *global coordinate system* is represented *locally* at the center of the field. Systematic errors are not included, nor are random errors of individual target sources.

2.5. What is an astrometric telescope?

All real-world observations have *systematic errors*. Almost all astronomical telescopes can be used to obtain positions of celestial objects (this process is often called "astrometry"[1]) to *some* extent. However, an astrometric telescope is an instrument *designed* for high astrometric accuracy, including *hardware features* to detect and *control systematic errors*.

A transit circle instrument has a long list of such features like multiple microscopes for reading circles, reversal of telescope tube, mercury mirror for nadir observations and mark houses to control azimuthal errors. The Hipparcos satellite had 2 apertures and tight "basic angle" control and a laboratory calibrated focal plane grid which enabled wide-angle measures. Astrometric astrographs have a flat focal plane with low optical distortions and very small color errors. Often they also feature diffraction gratings and reversal options to control magnitude-dependent systematic errors as well as fiducial marks to determine tilt.

3. The UCAC project: going robotic

3.1. Overview and instrument

Prior to the official project start (Gauss et al. 1996) a feasibility study was undertaken in 1995 (Zacharias 1997), followed by almost 2 years of in-house upgrading the USNO 8-inch Twin-astrograph toward a robotic telescope (Rafferty, Germain & Zacharias 1997). The 5-element lens corrected for the red spectral passband is used for the survey imaging (f=2m, f/10). The visually corrected lens is used for guiding with an ST-4 unit and Barlow lens. A 4k by 4k CCD camera (Spectral Instruments, Kodak chip) was used for the 1998 to 2004 all-sky survey (CTIO, Chile and NOFS, Arizona).

Figure 1 shows the back end of the UCAC astrograph. The 4k camera with liquid cooling line is seen in the lower part of the picture. Above it the x,y slide with ST-4 is seen together with extensive wiring for motors and limit switches. A front view of the telescope is shown in Figure 2 with the 2 parts of the Hartmann screen open. For focusing they are closed automatically, leaving 4 holes.

[1] I prefer to restrict the use of the term "astrometry" to the state-of-the-art science toward "best" positions and motions, i.e. specifically dealing with systematic errors. A wording like "deriving positions" is appropriate for casual applications of standard, astrometric reduction procedures.

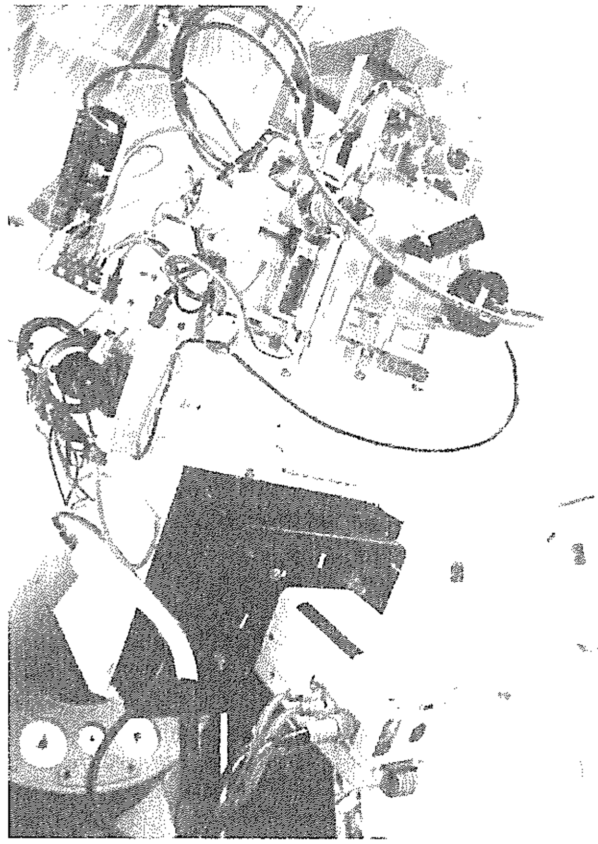

Fig. 1. Back end view of the UCAC Twin astrograph.

3.2. Hardware-software interface and operations

A diagram of the hardware control setup is shown in Figure 3, software details are given in Zacharias & Zacharias (1999). The telescope can observe a list of fields automatically. A simple target selection is implemented: the field with the lowest declination in a small hour angle window around the meridian is selected from the nightly list. Then sequentially the telescope is moved in RA and Dec. Next the x,y slide at the guide scope is automatically set to an *a priori* selected, optimal guide star and the ST-4 inquired. The telescope pointing is iterated whenever the offset is larger than about 15 arcsec. Then the ST-4 starts guiding and after a delay of about 20 sec the first exposure begins at the 4k camera. With direct memory access (DMA) the image of the camera is read into PC1 (16 sec) after which a short exposure is taken on the same field while the ST-4 continues to guide. For the about 125 + 25 sec integration time the total overhead time is about 120 sec, resulting in a throughput of about 13 fields (26 exposures) per hour.

After a pair of exposures has been acquired, the telescope moves on to the next field while the compressed 4k CCD frames are ftp'ed to our workstation. A daemon checks for new incoming images and then performs a quick data reduction, including matching of fitted x,y positions to Tycho reference stars. A line is added to a quality control file. The last

Fig. 2. "Red" and "yellow" lens of Twin astrograph with objective grating and Hartmann screen (for focusing) open.

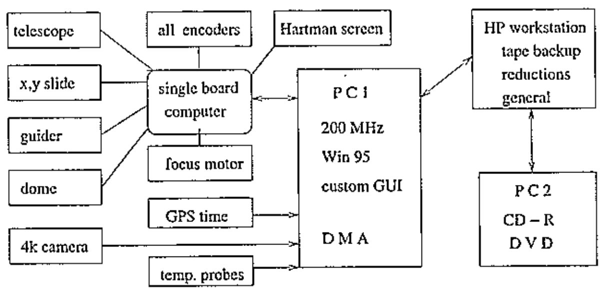

Fig. 3. USNO astrograph control flow used from 1997 until present.

dozen lines are then displayed for the observer to assist in quality control measures.

3.3. Need for an observer

An observer is present during the night to perform the following tasks:

- open and close dome, power up and down the system
- start focus sequences
- start automatic observing mode
- change ST-4 settings
- follow the quality control output and e.g. change exposure times as a function of transparency and seeing
- interrupt automatic observing in case of clouds or poor conditions
- act on error messages and re-start (part of) the system
- run backups to CDs and DVDs (previous night data)
- run custom verify code on backups

3.4. Experiences and problems

Most frequent were DMA errors. The operating system of PC1 was modified to increase the reliability; however, about 5% of frames do not arrive properly at PC1. Most of these cases will be handled automatically, and the telescope control initiates a re-take for the missing frame. Sometimes the entire PC1 crashes and a reboot by the observer is required.

The next vulnerable item in our setup is the communication between PC1 and the single-board computer (SBC), resulting in missing header info (most frequently temperature readings) or hangup of the auto-mode. The decision was made at the end of 1997 to go ahead with the then existing system and have an observer to "babysit" the operations. The alternative would have been to spend an uncertain amount in time and money to make the system fully robotic and delay the survey.

The survey started in February 1998 and was completed in May 2004. The 4k camera took over 275,000 exposures, about 4.5 TB of compressed raw data. The entire relocation of the instrument from Cerro Tololo, Chile to Flagstaff, Arizona cost 42 nights, most of which were spent on an airport in Santiago to wait for the right cargo plane. The total down time due to instrumentation problems was in the order of 2% of the available night time. This large up-time was achieved with regular maintenance on the instrument, e.g. by cleaning the mechanical relays every 6 months, and having an instrument shop available in the day time during critical periods.

The part with the largest failure rate was the shutter for the 4k camera. Of the 2 units we have, 1 was out on repairs most of the time. The biggest data managing problem we encountered was finding reliable backup media. In the beginning we easily could write 2 copies to exabyte 8mm tapes. Writing a CD-ROM was a challenge. Close to the end of the project there were no longer 8mm tape drives for sale and copying all data to DVD had begun. A few percent of the tapes are no longer readable and handling over 6,800 CDs (single copy) is awkward. We are now in the process of loading all raw data to RAID hard disk arrays for reprocessing toward the final catalog.

3.5. Data release and systematic errors

The UCAC2, containing positions and proper motions of 48 million stars (86% of sky), was released at the IAU GA in Sydney (Zacharias et al. 2004). All sky observing was completed in May 2004 and the final catalog is expected in 2006. For the about 10 to 14.5 magnitude range the positions are accurate to 20 mas per coordinate at their mean epoch of observation, with a limiting magnitude of about R = 16 and 70 mas accuracy.

Systematic errors were mainly controlled by

- center-corner overlap pattern of fields
- long + short exposure on each field
- narrow passband (579–642 nm)
- fixed filter used as dewar window, resulting in a stable field distortion pattern
- use of "on-axis" area (central 1° of 9° diameter field of view of telescope)
- frequent observation of calibration fields, including flip of the telescope (180° w.r.t. the sky)
- flip of camera by 90° at begin and end of survey with additional calibration field observations

By far the largest systematic error in the raw data is introduced by a low charge transfer efficiency of our particular chip. This results in magnitude times coordinate type errors up to 100 mas, which could be controlled to the 10 mas

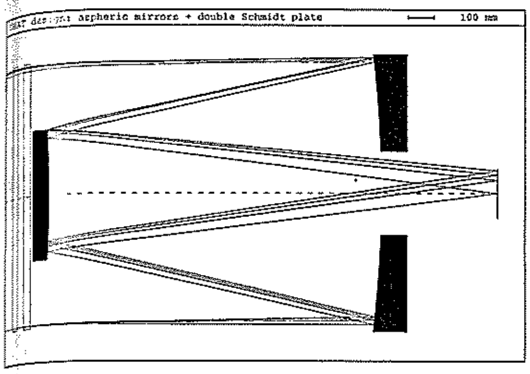

Fig. 4. Preliminary optical design of URAT.

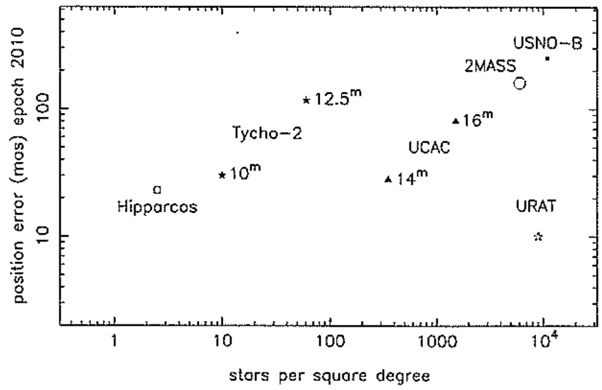

Fig. 5. Performance of reference star catalogs in comparison.

level. For details see the UCAC papers (Zacharias et al. 2000, 2004).

4. The URAT plan

The USNO Robotic Astrometric Telescope (URAT) is the next step toward fainter, more accurate reference stars (de Vegt, Laux & Zacharias 2003). The optical design is sketched in Figure 4. It is an astrometric telescope of about 0.9 m aperture, 3.6 m focal length and a circular symmetric pupil (no spider construction in the light path). The secondary mirror is mounted with the double corrector plates. No "field corrector" is required for this very low distortion design optimized for the 550 to 750 nm spectral passband with insignificant color errors.

A single, monolithic detector (6 or 8-inch full-wafer) is envisioned for the about 3° diameter field of view. This will allow for a gap-free coverage of about 4 square degrees per exposure. With a critical sampling of about 2 pixel/FWHM at 1.0 arcsec seeing, a pixel size of about 9 μm is required. The almost ideal mapping properties allow use of a simple reduction model, thus increasing the astrometric accuracy even in case of a relatively low weight from reference star positions.

Optical design studies are in the final phase and blanks will likely be ordered by the end of 2004. For the focal plane development research money could be secured. A traditional CCD detector and a CMOS/PIN hybrid are under investigation. The hybrid takes advantage of "good" properties of both technologies: a silicon diode array, similar to a CCD is used for photon detection (with high quantum efficiency and fill factor). A CMOS readout structure is attached to address individual pixels without charge shifting and no charge bleeding.

Features to observe bright stars will be implemented, allowing the determination of 5 to 10 mas accurate positions for naked-eye stars. The nominal survey operation would include long exposures (about 300 sec) reaching beyond 20th magnitude, thus covering most of the ICRF counterparts directly.

URAT will be a fully robotic instrument, likely with command-line type interface. The plan is to start observing in the southern hemisphere at a well-developed site with technical support. Figure 5 shows the expected vast improvement of a URAT-type reference star catalog as compared to existing standards.

Due to proper motion errors the random position errors of Hipparcos stars will be well above 20 mas per coordinate by the year 2010. The Hipparcos Catalogue Reference System (HCRS) is expected to be aligned to the ICRF on the 5 mas level by that time. With the dedicated observations of ICRF sources, URAT will even improve the optical *system*. Block adjustment reduction techniques (Zacharias 1992) will allow to link to the quasars directly, thus also providing for the zero-point of absolute trigonometric parallaxes, which will be detectable for many stars.

A URAT catalog will eventually be superseded by a space mission like GAIA (catalog release expected in 2019). The Space Interferometry Mission (SIM) with an expected launch date in 2010 will establish a much better stellar reference frame than URAT can ever provide. However, SIM is a pointed mission with about 20,000 targets only, while URAT will reach a billion stars and galaxies. URAT could very well utilize SIM as a reference star catalog.

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